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I HEREBY CERTIFY THAT THIS CORRESPONDENCE IS BEING DEPOSITED WITH THE UNITED STATES POSTAL SERVICE AS FIRST CLASS MAIL IN AN ENVELOPE ADDRESSED TO: ASSISTANT COMMISSIONER OF PATENTS AND TRADEMARKS, WASHINGTON, D.C. 20231, ON THE DATE INDICATED BELOW.

Amy M. Weiner

ATTORNEY FOR APPLICANT

1-9-02

DATE OF SIGNATURE

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In the Application of:	LOWENSTEIN, M.	Group Art Unit: 2836
on:	ELECTRICAL FILTER/PROTECTOR, AND METHODS OF CONSTRUCTING AND UTILIZING SAME	Examiner: HUYNH, K.
Serial No.:	08/422,360	
Filed On:	4/17/95	

Commissioner for Patents
Washington, D.C. 20231

DECLARATION OF JOHN A. DeDAD

I, John A. DeDad, hereby declare and state as follows:

1. I am employed by Primedia Business Magazines & Media as Editorial Director of Electrical Construction & Maintenance (EC&M) Magazine, CEE News Magazine, Electrical Wholesaling Magazine, and Electrical Marketing Newsletter as well as Conference Director of EC&M Seminars. Primedia publishes trade publications in all the major industry sectors. EC&M and CEE News Magazines' editorial content is based on electrical construction and engineering, with EC&M having highly technical articles and CEE News having industry-related news

articles. Both magazines cover the National Electrical Code. I was hired as a Senior Editor for EC&M in 1989, promoted to Managing Editor in 1991, then Editor-in-Chief in 1993, and finally Editorial Director in 1999. Throughout my career at Primedia, I have followed the problem of harmonics, beginning with the landmark articles (copy attached) "Nonlinear Loads Mean Trouble" (EC&M, March 1988 issue) and "Double the Neutral and Derate the Transformer - or Else" (EC&M December 1988 issue), both written by then EC&M Senior Editor Arthur Freund. Upon Mr. Freund's retirement in 1990, I assumed the responsibility of specializing in writing articles and presenting seminars on the subjects of Power Quality and Harmonics. I was a presenter at four Harmonics & Power Quality Conferences (sponsored by EC&M Seminars) and at least 10 Electric and Electric West Shows (sponsored by EC&M Magazine; owned by Continental Exhibitions, New York City). I have studied the various technologies available of preventing the problems caused by single- and three-phase nonlinear loads and the harmonic currents they generate.

2. The term "INVENTION" as used herein means the devices defined by the following claims 22, 26, 29, and 39 of the above-identified patent application:

"22. In a multiple phase electrical system for supplying power from an AC source to one or more nonlinear loads connected to at least one phase line therein, a device for substantially eliminating currents in a neutral wire, said device comprising:

a first completely-passive parallel resonant circuit having three passive electrical branches connected in parallel;

said first completely-passive parallel resonant circuit is tuned to a third harmonic frequency of a fundamental frequency of said AC source; and

said three passive electrical branches comprise a first branch consisting of a capacitor, a second branch consisting of a reactor, and a third branch consisting of a resistor.

26. A device according to claim 22, wherein:

each phase line of said multiple phase electrical system supplies power to an associated one of said nonlinear loads;

said device includes a second completely-passive parallel resonant circuit and a third completely-passive parallel resonant circuit;

each of said first, second and third completely-passive parallel resonant circuits is connected along a separate phase line of said multiple phase electrical system in series with at least one of said nonlinear loads whose power is supplied by said separate phase line; and

each of said first, second and third completely-passive parallel resonant circuits is tuned to said predetermined harmonic frequency of said fundamental frequency of said AC source.

29. A device for substantially eliminating a predetermined harmonic current generated by a nonlinear load in an electrical distribution system which distributes power from an AC source, said device comprising:

a completely-passive parallel resonant circuit connected in series with said nonlinear load;

said completely-passive parallel resonant circuit comprises three completely-passive electrical branches;

said completely-passive parallel resonant circuit is tuned to a third harmonic frequency of a fundamental frequency of said AC source to change the current drawn by said nonlinear load; and

said three completely-passive electrical branches comprise a first branch consisting of a capacitor, a second branch consisting of a reactor, and a third branch consisting of a resistor.

39. A device for reducing currents in an electrical system which supplies power to a nonlinear load from an AC source, comprising:

a completely-passive parallel resonant circuit connected in series with said nonlinear load;

said completely-passive parallel resonant circuit comprises three completely-passive electrical branches;

said completely-passive parallel resonant circuit is tuned to a third harmonic frequency of said AC source to change the current drawn by said nonlinear load;

a housing member for said completely-passive parallel resonant circuit; and

means for connecting the nonlinear load to said completely-passive parallel resonant circuit."

3. I first became aware of Harmonics Limited (the assignee of the above-identified patent application), its products, its technology, and the INVENTION through a Harmonics & Power Quality Conference in the early 1990s, where Dr. Michael Lowenstein (the applicant of the above-identified patent application) of Harmonics Limited was a presenter. His discussion of the problem of triplen harmonics and the INVENTION to eliminate the problem led to many articles written for the EC&M column PQ Corner by Ray Waggoner, starting with the multi-part article (copy attached) "Beware of Single-Phase Harmonic Interactions" (June, July, August 1994 issues of EC&M).

4. Prior to the introduction of the INVENTION, the main technique of addressing the triplen harmonic problem was to cope with it. A great many articles focused on coping were

featured in EC&M prior to 1994, some of which I wrote and presented at various shows and conferences. The technique of coping involved increasing the physical robustness of the electrical distribution and/or branch circuit system. The INVENTION permitted the elimination of the triplen harmonic problem.

5. Harmonics Limited has advertised only twice in EC&M Magazine, in the September and October 2000 issues. Prior and subsequent to these issues, Harmonics Limited has had no major advertising programs in any Primedia magazine.

6. The commercial success of the INVENTION is based on the advantage of its technology, which eliminates the need to replace existing branch circuit wiring or increase neutral conductors, and redistribute existing loads on existing delta-wye transformers. The installed cost of the above coping methods is saved through the application of the INVENTION. Other technologies involve the use of tuned filters in harmonics mitigating systems that are application unique, depending on the harmonics present and their magnitude.

7. In review of the many products featured in EC&M Magazine's New products section from 1989, I have not seen any other product or technology similar to that of the INVENTION. Also, in my prior activities as presenter on the topic of Harmonics and Power Quality at the major electrical construction industry shows and conferences, I have not seen and was not aware of any other engineers skilled in the field that were using the INVENTION. If the INVENTION was indeed obvious, I would have seen products using the INVENTION submitted in press releases to EC&M Magazine for inclusion in the magazine's New Products Department. Also, I would have received case history and/or technology articles that would have detailed the INVENTION and/or very similar technology, product performance, and capabilities.

8. I declare that all statements made herein of my own knowledge are true and all statements made on information and belief are believed to be true; and, further, that these statements were made with the knowledge that willful false statements and the like are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the above-identified application and any patent issuing thereon.

Dated: 12/9/01

John A. DeDad

John A. DeDad

NONLINEAR LOADS MEAN TROUBLE

Arthur Freund, Senior Editor

What nonlinear loads are and how they radically affect neutral sizing, equipment ratings, and load measurements.

NONLINEAR ELECTRICAL LOADS have expanded rapidly in recent years. This has led to serious and unexpected problems, such as failure of transformers and generators loaded well below their maximum ratings, and severe overheating of full-size neutral conductors. These new loads behave differently from normal loads and require a revision of thinking in design and application of equipment to avoid failures.

Types of loads

Motor, incandescent lighting, and heating loads are linear in nature. That is, the load impedance is essentially constant regardless of the applied voltage. For alternating current, the current increases proportionately as the voltage increases and decreases proportionately as the voltage decreases. This current is in phase with the voltage for a resistive circuit with a power factor (PF) of unity. It lags the voltage by some phase angle for the more typical partially inductive circuit with a PF commonly between 0.80 and 0.95, and leads the voltage by some phase angle for the occasional capacitative circuit, but is always proportional to the voltage (Fig. 1). For a sinusoidal voltage, the current is also sinusoidal.

Until recently, almost all loads were linear, and those that were not were such a small portion of the total as to have little effect on system design and operation. Then came the electronic revolution and electronic loads, such as computers, UPS equipment, and variable-speed motor drives, have proliferated. These electronic loads are mostly nonlinear, and they have become a large enough factor to have serious consequences in our distribution systems. Overheated neutral conductors, failed transformers, malfunctioning generators, and motor burnouts have been experienced, even though loads were apparently well within equipment ratings.

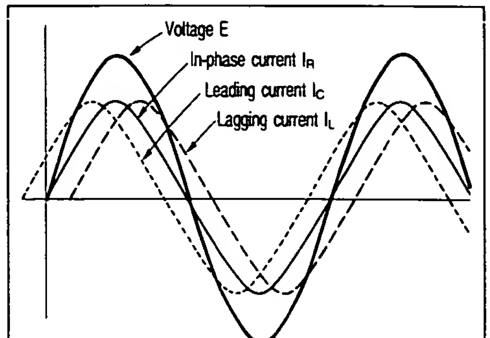


Fig. 1. Linear currents.

A *nonlinear load* is one in which the load current is not proportional to the instantaneous voltage. Often, the load current is not continuous. It can be switched on for only part of the cycle, as in a thyristor-controlled circuit; or pulsed, as in a controlled rectifier circuit, a computer, or power to a UPS. The major effect of nonlinear loads is to create considerable harmonic distortion on the system. These harmonic currents cause excessive heating in magnetic steel cores of transformers and motors. Odd-order harmonics are additive in the neutral conductors of the system, and some of the pulsed currents do not cancel out in the neutral, even when the three phases of the system are carefully balanced. The result is overloaded neutral conductors. Also, many of these nonlinear loads have a low PF, increasing the cost of utility power where PF penalty clauses apply. Nonlinear load currents are nonsinusoidal, and even when the source voltage is a clean sine wave, the nonlinear loads will distort that voltage wave, making it nonsinusoidal.

It is essential that special characteristics of

Computer terminals in office buildings have become so numerous that the harmonic currents drawn by their switching power supplies create significant loads and sometimes overloads on the neutral conductors, even when the loads on the three phases are balanced.

nonlinear loads are understood so that failures on critical systems are avoided.

Sources of harmonics

AC-to-DC converters (rectifiers). In rectifiers for DC loads and DC motor speed controls, the incoming AC is rectified and in many cases filtered to remove the ripple voltage.

In AC speed controls, the incoming AC is rectified to DC, which is then inverted by pulsing circuits back to adjustable-frequency AC. The same steps are used in UPS systems to obtain constant-frequency 60 or 415 Hz AC power.

In power supplies for computers, office machines, programmable controllers, and similar electronic equipment, the AC is converted to low-voltage DC, with high-speed switching circuits for controlling the voltage. The DC is used directly by the microprocessors or central processing unit (CPU).

In the past, most motor-driven computer peripherals, such as tape drives and cooling fans, had AC motors. However, in the latest equipment these peripherals use DC motors, increasing the DC load of the computer system.

Conventional rectifier-type power supplies consist of a transformer to raise or lower the voltage, a rectifier, and filtering to remove the voltage variations or ripple from the DC output. A simple single-phase rectifier circuit is shown in Fig. 2. Where voltage change is not necessary, the transformer may be eliminated. Voltage control can be obtained by replacing the diodes in the rectifier with thyristors (silicon-controlled rectifiers or SCRs). These are gated on (conducting) at any point in the cycle, turn off automatically as the voltage passes through zero, and are gated on again at the same point in each subsequent half-cycle.

Three-phase rectifiers consist of three single-phase circuits for a six-pulse rectifier, or use transformers to increase the number of phases to create a 12- or 24-pulse circuit. The greater the number of pulses, the less filtering is needed to provide a smooth, ripple-free DC output. There are many variations of these basic rectifier circuits.

A characteristic of all rectifier circuits is that they are nonlinear and draw currents of high harmonic content from the source. Diode full-wave rectifiers are least nonlinear, conducting as soon as the forward voltage overcomes the small (about 0.7V) forward bias required. Phase-controlled rectifiers using thyristors do not begin to conduct until gated on and are therefore more nonlinear. Most electronic equipment uses capacitor-input filters, which are more nonlinear than reactor-input (choke-input) filters. The characteristics of the load may also increase the nonlinearity of the input current.

Switching-mode power supplies (SMPS). The standard power supply, with a transformer and an iron-core choke in the filter, is large, heavy, inefficient, and costly. Manufacturers of computers and other microprocessor-based electronic equipment have almost completely changed over to the switching-mode type of power supply, which eliminates the heavy iron-core input transformer and filter choke. A simplified SMPS circuit is shown in Fig. 3.

The switcher controls the voltage, switching at a frequency of from 20 to 100kHz. Some newer switchers operate in the MHz range. A transformer on the switcher output provides some voltage control and isolation of the load from the source. The high switching frequency means that the transformer can be small and light. It requires only a ferrite core instead of a steel core. Voltage sensors and control circuits vary the switcher duty cycle (ON time) to produce the required output voltage under varying load conditions.

The SMPS is highly nonlinear and a major source of harmonic distortion and noise. The high-frequency harmonics extend into the radio-frequency (RF) range, requiring most manufacturers to include filters in the incoming line to meet FCC requirements on limiting conducted and radiated interference. Modern computers, from the individual PC to the largest

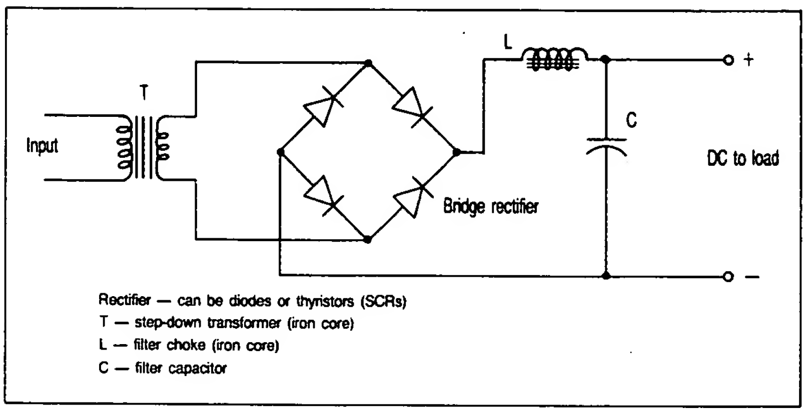


Fig. 2. Single-phase rectifier circuit.

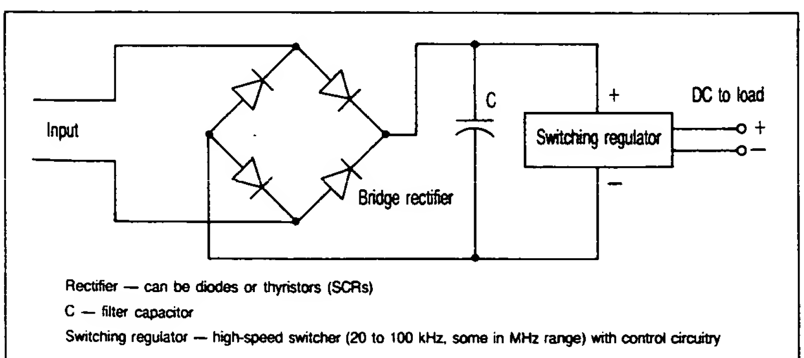


Fig. 3. Switching-mode power supply circuit.

mainframe, and most other microprocessor-based electronic equipment use SMPS and are a major source of nonlinear load problems.

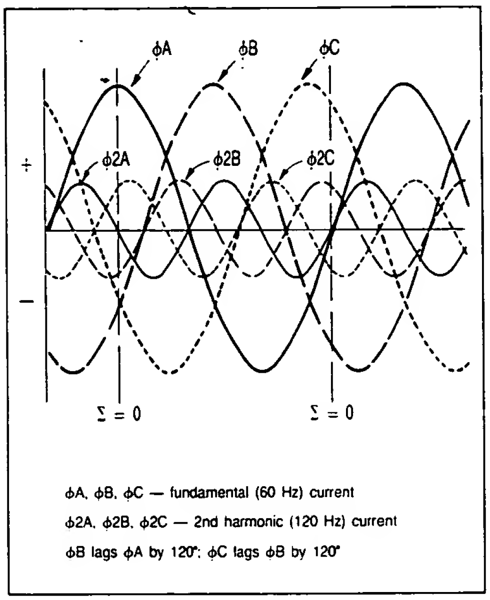
Neutral currents

Harmonics are currents (or voltages) at integral multiples of the fundamental frequency, which for power in the United States is 60 Hz. The 2nd harmonic would be 120 Hz, the 3rd harmonic would be 180 Hz, the 5th harmonic would be 300 Hz, the 11th harmonic would be 660 Hz, and so on. It is common knowledge that odd-order harmonic currents are additive in the common neutral of a 3-phase system, but the mechanism that causes this is little understood.

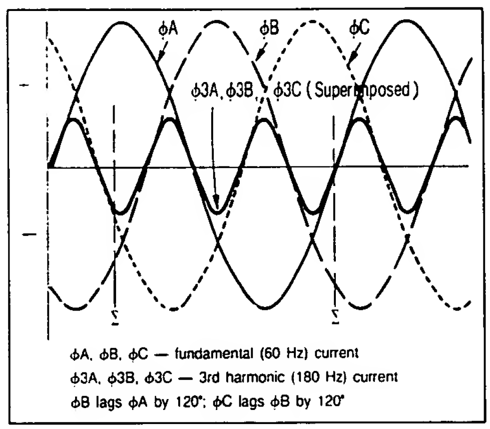
In a 3-phase, 4-wire system, single-phase line-to-neutral load currents flow in each phase conductor and return in the common neutral conductor. The three 60-Hz phase currents are separated by 120°; and for balanced 3-phase loads, they are equal. When they return in the neutral, they cancel each other out, adding up to zero at all points. Therefore, for balanced 3-phase, 60-Hz loads, neutral current is zero.

For 2nd harmonic currents separated by 120°, cancellation in the neutral would also be complete (Fig. 4A), with zero neutral current. This is true in the same way for *all even harmonics*.

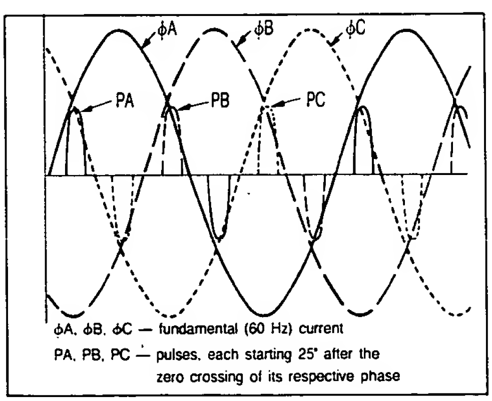
For 3rd harmonic currents, the return currents from each of the three phases are in



4A. Fundamental and 2nd harmonic currents. At any point, the sum (Σ) of the positive (+) and negative (–) currents equals zero for the fundamental current, the 2nd harmonic current, and, in similar fashion, all even harmonic currents. Therefore, for balanced 3-phase loads on a 3-phase, 4-wire system, no 60-Hz or even harmonic currents flow in the common neutral.



4B. Fundamental and 3rd harmonic currents. 3rd harmonic currents are equal and in phase (the curves are superimposed). At any point, the sum (Σ) of the equal 3rd harmonic currents equals three times the value of any one of the currents. This is also true for all odd multiples of the 3rd harmonic (9th, 15th, 21st, etc.). Other odd harmonics are also additive, but not fully, since they are equal but not exactly in phase. The total neutral current for other odd harmonics (5th, 7th, 11th, etc.) is more than any one harmonic phase current, but less than three times any harmonic phase current.



4C. Fundamental and pulsed currents. The sum of the pulses in the neutral equals three times the RMS value of any one phase pulse, since there is no overlap or cancellation. Different pulses might overlap for partial reinforcement or cancellation. The RMS current in the neutral depends on each single-phase pulse RMS current, and the pulse shape, frequency, and duration.

Fig. 4. Neutral currents in balanced 3-phase systems.

phase in the neutral (Fig. 4B), and so the total 3rd harmonic neutral current is the *arithmetic sum* of the three individual 3rd harmonic phase currents. This is also true for *all odd multiples of the 3rd harmonic* (9th, 15th, 21st, and so on). Other odd harmonics (5th, 7th, 11th, 13th, and so on) add in the neutral, but the total neutral-harmonic current is somewhat less than the arithmetic sum of the three harmonic phase currents. Mathematically, the total is the vector sum of the three currents. The phase angles between the three phase currents result in partial addition and partial cancellation.

The theoretical maximum neutral current with harmonics is at least 1.73 and perhaps as much as 3.0 times the phase current. (There is dispute as to the true maximum value between these limits. Research is being done to establish the correct value.) For pulsed loads, the pulses can occur in each phase at a different time. They will return in the common neutral, but they will be separated by time; therefore, there will be no cancellation. If *none* of the pulses overlap, the neutral current can be three times the phase current (Fig. 4C).

The effects of additive harmonics in the neutral were first recognized in the NEC many years ago, when Sec. 230-22 prohibited reduced neutral conductor size for that portion of the load consisting of discharge lighting. The effects of electronic equipment were recognized in the 1987 NEC when the prohibition in Sec. 230-22 against reducing the neutral was expanded to include loads from data-processing and similar equipment.

The severity of the problem can be seen in the true story of a major financial institution in New York that had a 225A computer supply panelboard with a 50A load per phase. The 225A incoming neutral conductor termination in this panelboard was a poor-quality connection, and it was glowing cherry red. Normally, with only a 50A balanced load on the phases, even a poor 225A neutral connection would not develop an excessive temperature. Because the company could not afford to shut down its critical computers, they had a maintenance "bucket brigade" cooling the neutral termination with CO_2 fire extinguishers for two days, until the computer functions were transferred to other equipment and the panel could be shut down.

There are several solutions to minimize this problem. First, not only must neutral conductor sizes *not* be reduced for these loads, but they must often be *increased*. Many engineers are designing with neutral conductors sized for at least 150% of the true RMS (root-mean-square) phase current, including the harmonic content. The Computer and Business Equipment Manufacturers Association (CBEMA) has a draft recommendation (not yet final) that the neutral of a 4-wire system supplying computers and business equipment have an ampacity at least 1.73 times the phase conductors, and that for simplicity the neutral can be two conductors of the size of the phase conductors—in other words, a double-ampacity neutral. It would not be surprising to see, in the near future, requirements added to the NEC for oversizing the neutral on supplies to electronic equipment.

Second, the harmonic content of the loads may be reduced by means of line filters. Since the manufacturers of the electronic equipment seldom install line filters beyond the minimum necessary to meet FCC requirements, the power-line filters must usually be separate units installed between the source and the loads. The filters, using tuned circuits to reduce each of the troublesome harmonics, require inductors or reactors and considerable capacitance. For large loads, harmonic filters are large and heavy, but they can supply a nonlinear load with relatively pure sine-wave voltage.

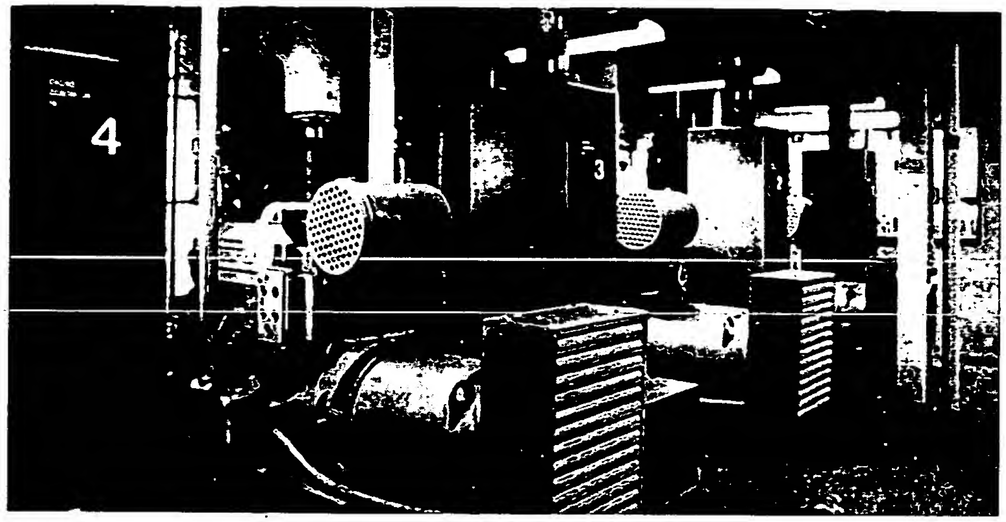
Third, for large computer, UPS, or other nonlinear loads, the final isolation transformer should be located as close as possible to the load. The neutral conductors from the wye secondary must be oversized as noted, but the conductor lengths would be relatively short. Nothing upstream from the transformer will be affected. However, the transformer may have to be derated.

Derating of transformers, generators, and motors

The ratings of transformers and generators are based on the heating created by load currents of an undistorted 60-Hz sine wave. When the load currents are nonlinear and have a substantial harmonic content, they cause considerably more heating than the same number of amperes of pure sine wave. There are two major reasons for this.

- When steel is magnetized, the minute particles known as magnetic domains reverse direction as the current alternates, and the magnetic polarity also reverses. The magnetizing of the steel is not 100% efficient, since energy is required to overcome the friction of the magnetic domains. This creates hysteresis losses, resulting in heat in the steel laminations of the core. The hysteresis losses are greater for a given RMS current at the higher-frequency harmonics, where the magnetic reversals are more rapid than at the fundamental 60 Hz.

Also, alternating magnetic fields induce currents into the steel laminations when the changing magnetic flux cuts through a conductor. These "eddy currents" flow through the resistance of the steel, generating I^2R eddy-current heating losses. Because of the higher frequencies, eddy-current losses are considera-



Engine generators are used to supply backup power to UPS systems before the battery power is depleted. For larger installations, multiple generators are paralleled. For UPS systems and other nonlinear loads, it is essential that the frequency and speed controls and the generator paralleling and load-sharing controls be designed to operate with loads of high harmonic content.

bly greater for harmonic currents than they are for the same RMS value of 60-Hz current.

• A lesser, but still considerable, heating effect at higher frequencies is caused by the "skin effect" in the conductors. Currents at higher frequencies are not distributed evenly through the cross-section of the conductor. The magnetic fields tend to force the current flow toward the outside or skin of the conductor. This effect increases as the frequency increases, and also as the magnitude of current increases. At higher frequencies, the center of the conductor carries little or no current. Therefore, the effective cross-section of the conductor is decreased, and its resistance is increased. It behaves as a smaller conductor of lower ampacity. As a result, a given current at harmonic frequencies causes more conductor heating than the same current at 60 Hz.

The result of hysteresis, eddy current, and skin effect is that the transformer or generator carrying no more than its full-rated RMS current, but supplying nonlinear loads with a high harmonic content, will overheat, sometimes to the point of failure. Transformers and generators loaded to less than 70% of their rating have been shut down because of overtemperature. Rectifier transformers specifically designed for nonlinear industrial rectifier loads have been manufactured to reduce these effects. At this time, transformers specially designed for other electronic loads are not available, and standard transformers must be derated.

As the harmonic currents are drawn by the loads, they act on the impedance of the source, causing harmonic distortion of the source voltage. Motors are normally linear loads, but when the supply voltage has harmonic distortion, the motors draw harmonic currents. These harmonic currents cause excessive motor heating from higher hysteresis and eddy-current losses in the motor laminations and skin effect in the windings. Thus, motors supplied from sources with voltage distorted by other nonlinear loads will also overheat unless they are derated.

The solutions to overheating of transformers, generators, and motors as a result of nonlinear loads are the same as those for neutral overheating. The equipment must be derated or the harmonic content must be reduced by line filters, or both. Unfortunately, there are no standards for the required derating, although considerable research is being done to determine these requirements. Derating can be done by observation, based on the temperature rises of the affected equipment. In initial design, equipment must be oversized by an amount determined by judgment and experience to permit the necessary derating.

Generator control problems

In addition to excessive heating, harmonic currents can cause other serious problems for generator installations. Modern generators use electronic means to regulate the output voltage of the generator, to control the speed of the engine or prime mover (and thus the output frequency of the generator), to parallel generators, and to share the load proportionately among the paralleled units.

Many of these control devices use circuits that measure the zero crossing point of the voltage or current wave. At 60 Hz this is fine; but with a high harmonic content, there may be many more zero crossings than the normal ones for 60 Hz. This can cause hunting and instability in speed and frequency control, and can make the paralleling of generators difficult or impossible.

Load sharing depends on measurement of the load on each unit. The RMS value of the current is simple to determine for a pure 60-Hz sine wave, but using controls based on 60-Hz RMS where harmonics are present will give

false readings, sometimes too high and at other times too low. Only more complex true RMS measurements will provide proper operation.

Therefore, it is urgent that the generator and control manufacturers are informed of the load characteristics if a generator is to be used alone or in parallel with nonlinear loads. If this is not done, the installation may not perform properly and it may be costly to obtain correct operation.

UPS output harmonic distortion

When harmonic currents are drawn by the load, they cause voltage distortion of the source. Since the voltage drop across the source for a given current is proportional to the impedance of the source ($E = I \times Z$), the distortion caused by a given harmonic current is lower for a low-impedance source and higher for a high-impedance source.

Uninterruptible power supplies (UPS) are used to supply clean power to computers under all conditions, including total utility power failure. They range from large systems of thousands of kVA for major computer installations to small units of a few hundred VA for PCs. If the loads distort the power supplied by the UPS, then the power fed to the loads will not be truly "clean."

The output distortion of the UPS for a given load depends on the UPS design and output impedance. This is true whether the UPS is the static type or the rotary motor-generator type. Most UPS manufacturers specify the output distortion of their equipment; 5% total harmonic distortion (THD) is typical. However, many manufacturers add a disclaimer, such as "*Based on linear loads*" or "*For reactive and inductive loads.*" Such a disclaimer means that the THD figure only applies under linear load conditions. Before purchasing any UPS, make certain that it is capable of supplying the actual types of nonlinear loads to be connected to it. Discuss the prospective loads with the manufacturer because correcting problems may be costly.

Noise, resonance, and other problems

Harmonics from nonlinear loads can cause noise and resonance problems in electrical distribution and communications systems.

Noise results from harmonics at audio and sometimes radio frequencies being carried over the power lines and getting into telephone, communications, and data systems by induction, capacitive coupling, or radiation. These noise signals may cause problems many miles from their source. They can generate electromagnetic interference (EMI) in telephone and communications systems and create costly errors in data-transmission systems. As already mentioned, the FCC has set maximum power-line conduction and radiation standards for many types of electronic equipment, such as computers. However, there are other types of harmonic-generating nonlinear loads that do not come under the FCC standards. In all cases, filtering and shielding are required to minimize both conducted and radiated noise interference.

Resonance occurs when the inductance in the system and the natural capacitance of the system, or added capacitors such as for power factor correction, form a tuned circuit resonant at one or more of the harmonic frequencies occurring because of the nonlinear loads. These resonant circuits can build up unusually high voltages, causing insulation breakdowns and equipment failures. Also, resonant circuits can draw very high currents, overloading some portions of the circuit. Since the inductance and capacitance of a system are unpredictable and often variable, resonance effects are difficult to calculate. However, if they are severe, as is often the case, the results will often be grimly and painfully obvious.

Capacitor failure is another result of high harmonic content in a system. The reactance of a capacitor goes down as the frequency of the applied voltage goes up. At higher harmonic frequencies, the reactance of capacitors added to the system for power-factor correction or surge suppression can be so low as to constitute a virtual short circuit; and if the current available at these frequencies is high enough, capacitor failure will occur.

Premature tripping or failure to trip for solid-state overcurrent relays on circuit breakers or for other electronic relays can occur if the relays are not designed to measure true RMS values for the harmonic-distorted currents or voltages. Such relays will sense values too high and trip prematurely, or too low and fail to trip, depending on the waveform being measured. True RMS sensing-type relays are required for nonlinear loads.

Many unexplained difficulties and equipment failures in electrical systems can be traced to heating, noise, resonance, impedance, and other effects of harmonic voltages and currents.

Measurements

Measuring nonsinusoidal currents and voltages requires radically different techniques than those which have been used for sinusoidal waveforms. Conventional meters (analog and digital) measure either the average value or the peak value of the waveform, and then are calibrated to read the equivalent RMS value. The RMS value of a periodic wave is called its *effective* value; the RMS value of current or voltage is a measure of its true heating value in a resistance. For a sine wave, the RMS value is 0.707 times the peak value, or 1.11 times the average value (Fig. 5). A meter sens-

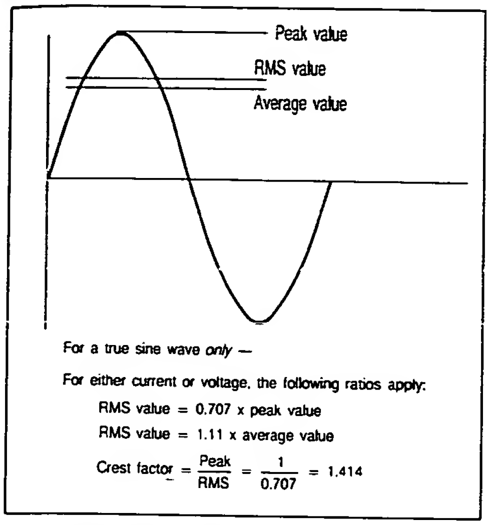


Fig. 5. RMS, peak, and average values in a sine wave.

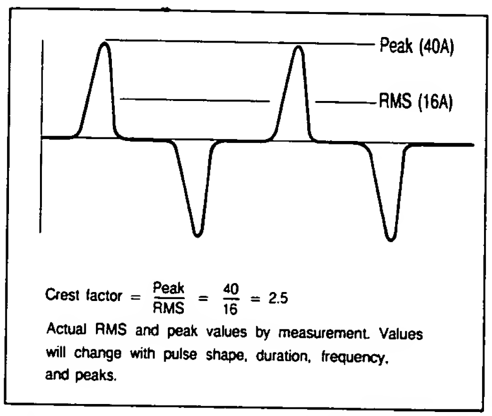
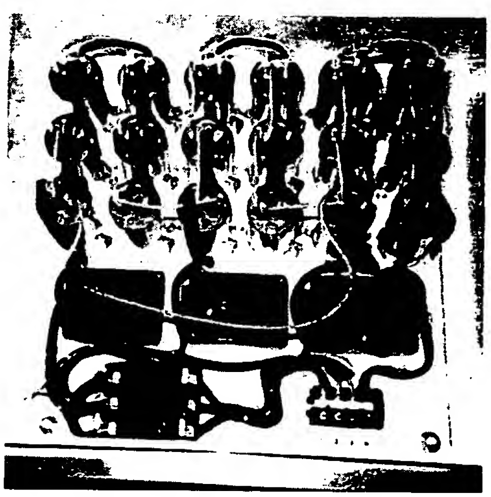


Fig. 6. RMS and peak values in a pulsed wave.



Harmonic distortion filter rated 30A, 3-phase, 208Y/120V, consists of circuits tuned to all odd harmonics from the 3rd (180 Hz) to the 17th (1020 Hz). It is often used in conjunction with a high-frequency noise filter for frequencies over 1000Hz. This 30A unit is in a 24-in.x24-in.x6-in.-deep enclosure. Tuned filters are available to at least 2000A. The enclosure for a 2000A unit is about 5 ftx5 ftx12 in. deep. Improvements in technology are permitting redesign of these filters, reducing their size.

ing peak or average values and calibrated using these multipliers to read RMS values will agree with a true RMS meter.

This is true only if the waveform being measured is a true sine wave. As soon as the waveform contains harmonics, the ratio of true RMS to average or peak value can change drastically. For example, on a square wave, the average-calibrated meter will read RMS values about 11% high, and the peak-calibrated unit about 30% low. For other waveforms, the error will vary. For pulses, the errors can be tremendous, depending on the height of the peak and on the off-time between pulses. The average-sensing meter will read very low (as much as 50%), and the peak-sensing meter will read very high (sometimes more than 100%).

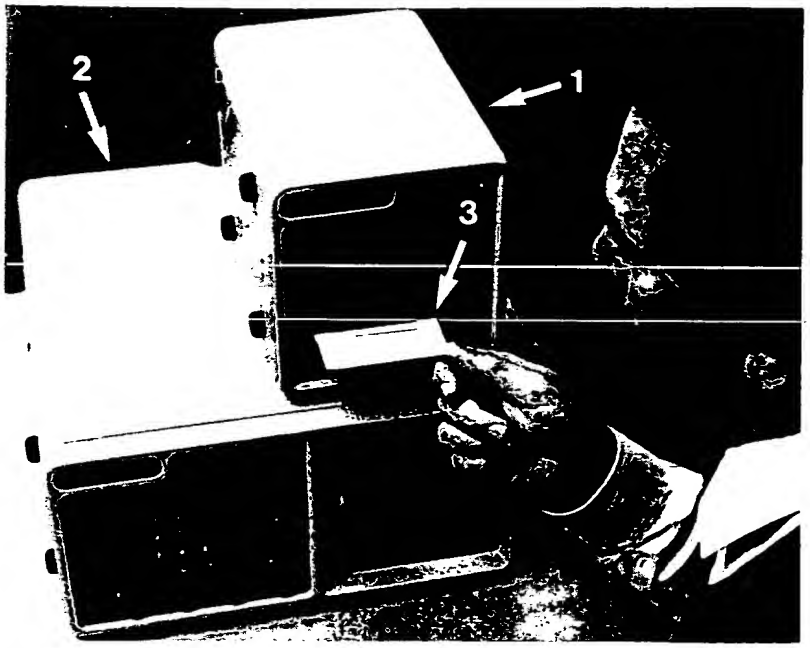
Crest factor is the ratio of the peak or maximum value of a waveform to the RMS value. For a pure sine wave, the crest factor is 1/0.707 or 1.414. However, for a pulsed wave of the same peak value, but with considerable "off" time and a low RMS value, the crest factor will be much higher (Fig. 6).

Only a meter or relay that measures true RMS values will give correct readings for a nonsinusoidal waveform. Thermal meters apply the input to a resistive load and measure the heat generated. This gives a true RMS reading, but is very slow in reaction time, and therefore not practical for most power system measurements. Some analog meters can be made to measure true RMS, but they are complex, slow, and limited in scope.

Accurate electronic measurement of RMS values has been made practical by microprocessors. RMS measuring circuits sample the input signal at a high rate of speed, typically about 100 times the highest harmonic frequency. To measure the 25th harmonic of a power system, a frequency of 1500 Hz, the sampling rate would be about 150,000 times per sec. The microprocessor circuits digitize and square each sample, add it to previous samples squared, and take the square root of the total. This will be an accurate RMS value, regardless of the waveform being measured. Practically, this cannot be done continuously, but is done to brief samples and is only possible using the high speed of digital electronic circuitry.

Current transformers must be of high quality (with a very wide bandwidth) to sense high and low frequencies accurately, if the RMS reading is to be accurate for high-order harmonics and pulsed currents. This is not a problem for pure 60-Hz sine waves.

The best designs of modern solid-state circuit breaker trips and of other electronic relays use this digital sampling technique and true RMS measurement, combined with high-quality sensors, to obtain accurate tripping on nonlinear loads. Older solid-state relays, even



Parallel processor (arrow 1) connects to power-line monitor (arrow 2) and provides graphic and tabular spectrum analysis printouts. It also stores up to 1400 graphs on IBM-compatible disks (arrow 3).

Initial Waveshape, Total Harmonic Distortion Report, and Spectrum Analysis Graph from Parallel Processor.

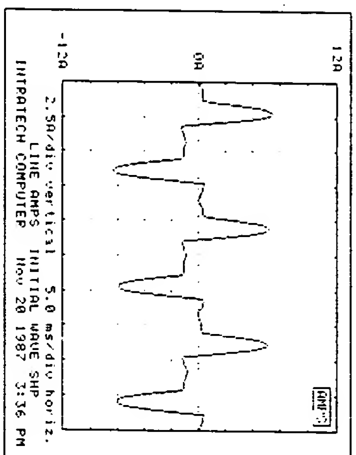
INTRATECH COMPUTER Nov 20 1987

HARMONIC REPORT 3:36 PM

LINE AMPS (Channel 2)
Current: 3.3 - 3.8 Amps

INTRATECH COMPUTER Nov 20 1987

LINE AMPS INITIAL WAVE SHP 3:36:45 PM



HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	0°	2nd	0.8%	88°
3rd	68.8%	217°	4th	1.4%	306°
5th	21.4%	76°	6th	0.4%	79°
7th	0.2%	113°	8th	0.2%	119°
9th	0.3%	285°	10th	0.1%	30°
11th	0.1%	228°	12th	0.2%	322°
13th	0.2%	24°	14th	2.0%	211°
15th	0.2%	57°	16th	0.2%	98°
17th	0.2%	24°	18th	0.9%	42°
19th	0.2%	328°	20th	1.0%	76°
21st	0.1%	63°	22nd	1.9%	275°
23rd	0.4%	65°	24th	2.5%	327°
25th	0.4%	178°	26th	0.2%	48°
27th	0.3%	155°	28th	0.8%	184°
29th	0.5%	183°	30th	0.3%	303°
31st	1.3%	69°			
ODD	72.1%		EVEN	4.4%	

THD: 72.2%

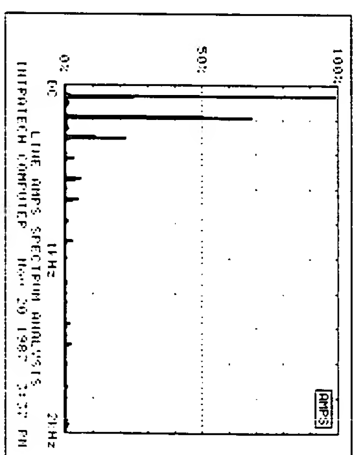


Fig.7. Graphic printout (on left) of initial wave shape, as recorded and printed out by the power-line monitor. Graphic and tabular spectrum analysis (on right) of the initial wave shape, as calculated by the parallel processor and printed out by the power-line monitor. Data is also stored on IBM-compatible disk for later examination.

though electronic, used average-sensing with RMS calibration. When applied on nonlinear loads, these relays can fail to trip on overcurrents or can trip unnecessarily.

When induction-disk watthour meters are applied on nonlinear loads, the harmonics may cause the disk to rotate faster or slower than the same RMS current at 60 Hz, depending on the specific harmonic content. If the watthour meter is used for billing, this can result in utility bills that are too high or too low—and in most cases, too high.

Power factor is the ratio between the true power consumed and the product of the voltage and the current ($PF = W/E \times I$, which can be transposed to $W = E \times I \times PF$). For a sine wave, the power factor is often expressed as the cosine of the phase angle between the voltage and current, and this equation becomes $W = E \times I \times \cos\theta$. This is true only for a sine wave, and $\cos\theta$ is not the power factor for nonlinear loads. The only accurate way to measure nonlinear power factor is to measure the average instantaneous power, and divide that by the product of the true RMS voltage and the true RMS current. This can be done by digital microprocessor circuits.

It is often important to know the actual harmonic content of a waveform. This information can be obtained by spectrum analysis, which breaks the waveform down into its separate harmonics and measures the percentage and the phase angle of each with respect to the fundamental frequency. This analysis has been made practical by digital microprocessor processing. Spectrum analyzers have recently become available that can print out the results in both graphic and tabular form (Fig. 7).

Recommendations

With the proliferation of computers and other electronic equipment, the problems of nonlinear loads and the harmonics they generate will not go away but will continue to get worse. A number of techniques can be recommended to minimize the effects of these loads.

- Oversize neutral conductors to between 150 and 200% of phase conductor ratings.
- Locate isolation transformers close to the load.
- Derate transformers, generators, and motors.
- Use true RMS sensing meters, relays, and circuit breaker trip units.
- Make certain that all controls, especially for generator speed and paralleling, will operate properly with nonlinear loads.
- Select power sources with low output impedances to minimize voltage distortion.
- Provide line filters to remove the harmonic loads from the source.

The effects of nonlinear loads on our power systems can no longer be ignored. ■

DOUBLE THE NEUTRAL AND DERATE THE TRANSFORMER—OR ELSE!

Arthur Freund, Senior Editor

CBEMA has issued an information letter explaining critical power problems from computer and electronic loads, with drastic recommendations to prevent damage to the distribution system.

COMPUTER AND BUSINESS Equipment Manufacturers Association (CBEMA, pronounced "seebeemah") is the electronic business equipment industry equivalent of the electrical industry National Electrical Manufacturers Association (NEMA). CBEMA became aware that the proliferation of switching-mode power supplies for computers and business equipment was resulting in large harmonic currents, and that these harmonics were causing severe and increasing problems in electrical distribution systems and equipment. (See "Nonlinear loads mean trouble" in *EC&M,* March, 1988). John Roberts, Manager of Corporate Power Standards for IBM, is chairman of the Power Subcommittee of the Environment and Safety Subcommittee of CBEMA. This subcommittee studied the problem and possible solutions, and CBEMA has issued an Information Letter containing their recommendations.

Because of its importance to the electrical construction industry, *EC&M* is reprinting below the entire text of this letter. *(Editorial comment and additional information or explanation not in the CBEMA letter appear in parentheses and italics.)*

EXECUTIVE SUMMARY

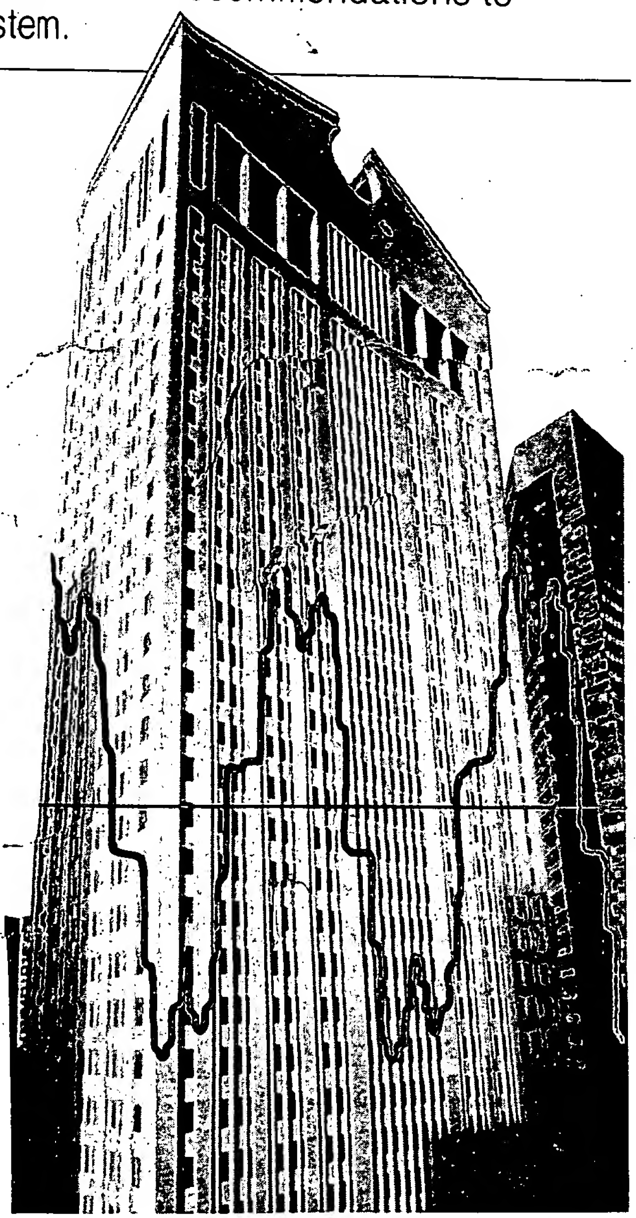
There has been a significant increase in the use of a new power conversion technology for Data Processing (DP) and Office Machines (OM).

This new highly efficient technology provides significant reduction in losses, weight, volume, and cost as well as much greater ride through capability. However, with these advantages, there are some potential problems for the unwary which must be recognized and handled.

There is increasing evidence that this new power technology, when used in data-processing and office machines, creates unanticipated harmonic currents.

When a large number of these single-phase products are operated from three-phase 208/120V power systems, which are commonly used in office buildings, there is the risk of overloading transformers and building wiring conductors, especially the neutral conductor. If the phase conductors are loaded to rating, the neutral conductor may be loaded to 173% of the rating.

Some of the consequences of these conditions may include building wiring failure, transformer overheating and failure, power factor correction capacitor failure, and deterioration of DP and OM equipment performance.



High-rise office buildings used to represent a fairly linear sinewave electrical load. Today, with electronic computers and other office equipment, solid-state lighting ballasts, motors with variable-speed drives for air conditioning and other systems, and similar nonlinear loads, the waveshape of the load current is badly distorted and high in harmonics. This situation and the resulting problems are getting steadily worse.

As a result, CBEMA has prepared the attached technical paper to alert and promote an understanding of the problem and its causes and to recommend measures that can be taken to reduce exposure. Those who may be affected by the possible existence of these problems include:

- Computer Room and Electronic Office Machine Area Managers,
- Their Installation Planners,
- Architects/Engineers,
- Consultants, and
- Electrical Contractors.

CBEMA INFORMATION LETTER

THREE PHASE POWER SOURCE OVERLOADING CAUSED BY SMALL COMPUTERS AND ELECTRONIC OFFICE EQUIPMENT

The Potential Problem:

The new, highly efficient power conversion technology commonly used in many small computers and electronic office machines has resulted in significant reductions in their power losses, physical size, weight, and cost. *(See the accompanying box.)* However, occurrences have been encountered where concentrations of these products on the same electrical wiring system within a building have been the cause of unexpected electrical problems. The most serious of these problems have occurred where these products, which require single-phase 120-volt power, are connected to 208/120-volt, three-phase/single-phase wiring systems. The problems range from overheating of building neutral wiring conductors, their connections, and transformers operating on the same system. Another possible side effect is the degradation of power quality by the creation of wave shape distortion. However, these potential problems and their consequences can be avoided if proper precautions are taken.

These problems are typically the result of harmonic load currents created by power supply rectifiers and capacitors in computers and electronic office machines connected between phase and neutral. Instead of load currents being proportional to the sinusoidally varying line voltage, these devices cause current to flow in a relatively short duration pulse during the peak of each voltage half cycle. If peak current is small in comparison to the current-carrying capability of the power

Switching mode power supplies

The new power technology referred to in the CBEMA letter is the use of *switching mode power supplies* (SMPS), sometimes called *switch-mode* power supplies or simply *switchers*.

Most modern electronic equipment using solid-state "chips" requires a DC power supply of between 3 and 15V. Until recently, this voltage was provided by a conventional power supply consisting of a step-down transformer, rectifier, filter, and voltage regulator (Fig. 1, typical). Transformer T_1 operates at 60 Hz to step the line voltage down to the AC voltage required to provide the desired DC voltage after rectification. The rectified DC is filtered by capacitors C_1 and C_2 and choke L_1 to provide smooth, ripple-free power. The main ripple frequency from the bridge rectifier BR_1 is 120 Hz. Voltage can be regulated by one of many regulator and control systems in the DC line, so this design is known as a *linear* or *series regulated* power supply.

Power is drawn from the source by the input transformer throughout the AC cycle, and the current waveform is relatively linear.

The new SMPS is very different (Fig. 2, typical). Incoming 60-Hz power is rectified at line voltage by bridge rectifier BR_2, and the high DC voltage is stored in capacitor C_3. The switcher and controls, usually transistorized, switch the DC voltage from C_3 on and off at a high frequency, which in various designs ranges from 10 to 100 kHz. These high-frequency pulses are stepped down in voltage by transformer T_2 and rectified by the diodes D_1 and D_2.

The low-voltage DC is filtered by capacitor C_4 and choke L_2. The ripple frequency of the DC output from the diodes is twice that of the switching frequency, ranging from 20 to 200 kHz. Because of the high switching frequency, transformer T_2 and the filter formed by capacitor C_4 and choke L_2 can be very small and light compared to their 60-Hz equivalents. The output voltage is controlled by the switcher, eliminating the series regulator and its losses.

As the load draws power, the switcher takes energy stored in capacitor C_3, lowering the capacitor voltage, and when the voltage from rectifier BR_2 exceeds the voltage on C_3, the re[illegible]ivers a pulse of current to the capacitor (Fig. 3). T[illegible]rts taking power from the source as the incom-

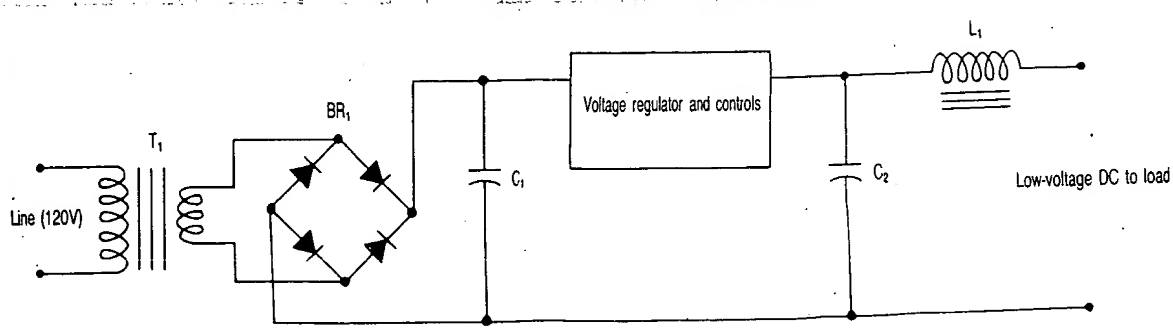


Fig. 1. Linear (series) regulator power supply

source and its conductors, no problem would be expected. However, if there are many such small loads or fewer larger loads, peak load currents can be substantial.

Problems which can result include:

1. Overheating of neutral conductors and connections, leading to failure of neutral conductors which could cause overvoltage damage to computers and electronic office equipment.

2. Intermittent electrical noise from connections which have been loosened by thermal cycling. This noise can be intense enough to corrupt digital circuit signals and cause malfunctions.

3. Transformer overheating, insulation damage and failure. *(John Roberts reports many transformer failures. In one case, a 300kVA transformer failed although a clamp-on averaging-type ammeter showed no overload. A 300kVA replacement transformer failed soon after installation. A true-rms ammeter showed a significant overload. A midwest utility reported a transformer failure where their transformer was not overloaded beyond its kVA rating, but where the customer's load was primarily motors with AC variable-speed drives of high harmonic content.)*

4. Distortion (peak voltage reduction) of line voltage waveshapes severe enough to impair the ride-through capability of computers and related equipment.

5. Overheating of motors operating on a distorted voltage source.

6. Nuisance tripping of circuit breakers.

(Other problems include failure of power-factor-correction capacitors, which provide a low-impedance path to currents with higher frequencies than the normal 60 Hz, thus carrying high harmonic currents. Also, the harmonic currents, acting on the impedance of the source, create harmonic distortion in the source voltage. This distorted voltage, applied to motors, has caused some motors to fail even though they were not overloaded, because of the presence of negative sequence currents from the harmonics as well as iron and winding overheating similar to that of transformers.)

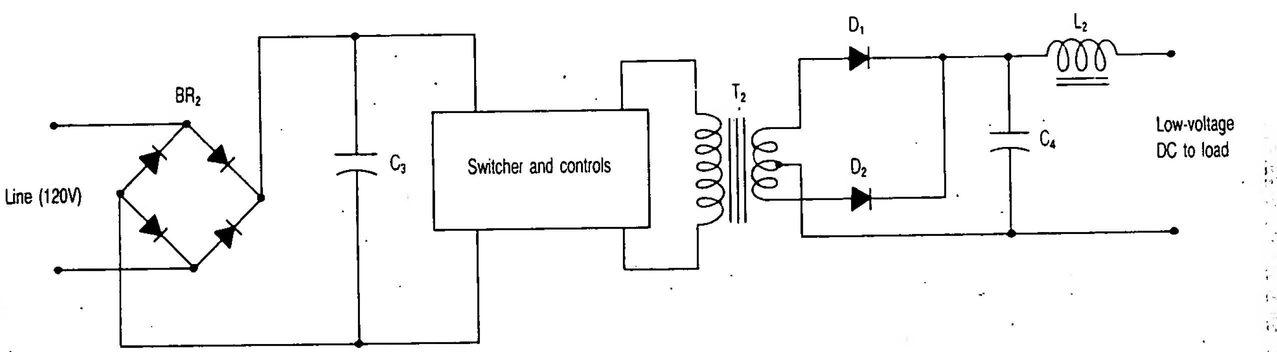


Fig. 2. Switching mode power supply

ing voltage approaches the peak of the sine wave and stops taking power when the voltage from the rectifier drops below the voltage on the capacitor, long before the incoming sine wave voltage reaches zero. These current pulses are extremely nonlinear and high in harmonics.

The switch-mode transformer and filter, operating at high frequency, are much smaller, lighter, and more efficient than the older design. Switcher voltage control has much lower losses than the series regulator. Overall switcher efficiency is about 75%, as opposed to linear supply efficiency of about 50%. Losses have been reduced by half, reducing operating costs and further reducing size by requiring less cooling. Better energy storage provides longer ridethrough, about 16 ms (one cycle) as compared to about 4 ms for the linear supply. The linear supply requires input voltage within 10% of nominal, while the switcher can tolerate voltage dips of about 20%.

With smaller size, higher efficiency, better ridethrough, less sensitivity to incoming power disturbances, and lower cost, the switch-mode power supply has almost completely replaced the linear supply for electronic equipment.

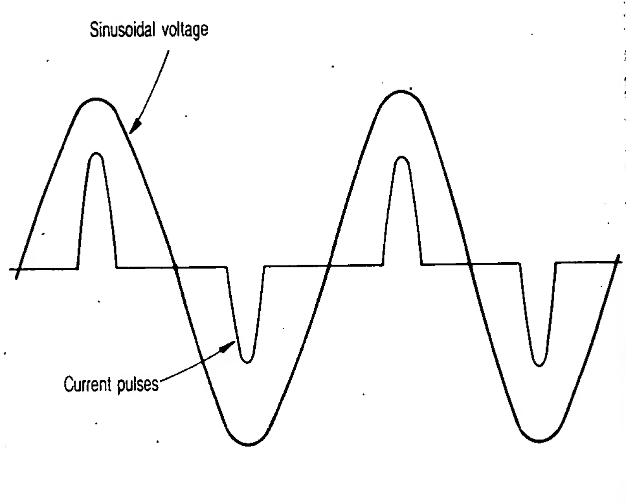


Fig. 3. Input to a switch-mode power supply

(CBEMA is concerned primarily with single-phase computer and business equipment loads. However, similar problems occur with any nonlinear loads. Other major nonlinear loads are rectifiers and equipment supplied by rectifiers, motor variable-speed drives, UPS systems, arc furnaces, solid-state ballasts for lighting, and any other electronic equipment using switch-mode power supplies. These loads can be either single- or 3 phase.)

Possible Causes of Overheating:

1. There may be more load current than indicated by a clamp-on ammeter. The most commonly used ammeters are "average actuated, rms calibrated," meaning that they measure true rms (root mean square) current only when the current is sinusoidal. When ammeters of this variety are used to measure nonsinusoidal (distorted) pulsed load currents, they typically indicate significantly less current than that which is actually flowing.

A "true rms" ammeter must be used to measure distorted currents. Otherwise, a circuit overload condition may not be detected except by overheated conductors or tripped circuit breakers.

2. Balancing phase line currents will not necessarily reduce neutral current.

Balancing the phase load currents in a 208Y/120-volt, three phase system (making load currents equal in each phase) will normally reduce neutral current to zero if load currents have an undistorted sinusoidal wave shape. However, when load currents occur in short pulses, they are rich in harmonics.

The 3rd harmonic and odd multiples of the 3rd (i.e. the 9th, 15th, etc.) will not cancel each other in the neutral. In fact, the neutral current consisting of these harmonics can be as high as 1.73 times the phase current. *(Under some conditions, the neutral current can be even higher, with a theoretical maximum of 2.73 times the phase current under very unusual conditions.)* If the neutral conductor is the same size as the phase conductors, the heating in the neutral can be as much as three times the heating effects present in each phase conductor.

3. Upstream three-phase transformers may be improperly sized and protected.

If these are three-phase, delta-wye transformers, each secondary wye leg conductor will carry the full output current of that phase winding. Currents in primary and secondary windings will be inversely proportional to their turns ratio and directly proportional to the load current. However, when the load is a source of harmonic currents, the third and multiples of the third harmonic will circulate in the delta-connected windings and not appear in the input line current to the transformer.

For this reason the input line current does not reflect the transformer's total load current, and the kVA input to these transformers can be less than the kVA output when loads are harmonic current sources. The transformer must be sized to carry the output kVA, which includes the circulating kVA, rather than merely the input kVA.

Unless the transformer contains approved thermal protection, the output circuit breaker must be sized to protect the transformer from overload. The input circuit breakers should be sized to protect against faults. Since input current is not a measure of the total kVA load in the transformer, the input circuit breakers cannot protect against overload. This protection must be provided by circuit breakers in the wye-connected secondary output circuits.

If the transformer is handling load currents which are rich in harmonics, the heating effect of those harmonics is significantly greater than if no harmonics were present. If a transformer is not designed for load currents with high harmonic content, it may overheat while appearing to be operating at less than its rating. *(In addition to heating from the circulating current in the delta primary winding, the higher frequencies of the harmonic currents cause greater hysteresis and eddy current heating losses in the steel of the transformer core and skin effect causes greater resistance heating losses in the winding. The result is that a given true-rms current at harmonic frequencies causes greater heating than the same true-rms current at 60 Hz. It is possible to design transformers to carry their full rated load with a heavy harmonic content. This has been done for years for arc furnaces. However, the standard transformer is designed for a pure 60-Hz sine wave and must be derated for loads with substantial harmonic currents.)*

A conservative method of selecting kVA size of a transformer for a given load, containing many switching mode power supplies, is based upon the load's steady state peak rather than rms current. Because energy transfer occurs essentially at the peak of the voltage wave rather than during the full cycle, the transformer's ability to deliver energy at the voltage peak without excessive internal voltage drop or heating are important considerations. Details are contained in Recommended Practices listed below.

Recommended Practices:

These recommendations address systems measurement, systems design, and remedies.

1. Use true rms ammeters to measure load currents in all phases and neutral.

2. If the steady state peak current is unknown, measure it with an oscilloscope and current probe. *(Several power monitors are now available that can provide a trace of the voltage or current wave shape, showing peak values, and also provide a complete harmonic content analysis of the wave in both graphical and tabular form.)* Measurement with moving coil or "peak hold" ammeters will give erroneous information.

3. Measuring instruments should have sufficient band width to provide accurate readings, taking into account the fundamental frequency and harmonic content of the parameters being measured. Current probes should be suitably rated for peak currents involved.

4. Select transformer ratings using the following basis. Where a substantial portion of the load consists of devices with single-phase switching mode power supplies, the transformer should be derated as follows:

1.414×rms Load Current divided by Peak Load Current.

This result is typically a factor of 0.5 to 0.7, but may be even lower where peak amperes are unusually high. *(This is equivalent to dividing the calculated peak value of the rms load current assuming it to be a true sine wave by the actual*

Microcomputers have proliferated in the typical office at an astounding rate. In many offices, nearly every desk has one. In addition, many other types of electronic office equipment add to the nonlinear load and the harmonic problems.

peak current of the load.) The transformer design and construction can affect the amount by which the maximum load must be reduced.

5. Run a separate neutral to 120 volt outlet receptacles on each phase. Avoid using a shared neutral conductor for single phase 120 volt outlets on different phases. *(The single-phase branch circuits can be run with a separate neutral for each phase, rather than using a multiwire branch circuit with a common or shared neutral. Electrical fires and neutral failures have been reported in some prewired office partitions that use multiwire branch circuits and supply many personal computers and office machines. At least one manufacturer of prewired partitions now wires them with a separate neutral conductor for each phase conductor to prevent neutral overheating. In any case, the feeder to the panelboard supplying these branch circuits will consist of three phases and a common neutral conductor. Overheating has frequently occurred in the neutral of the feeders and panelboards, as well as the branch circuits. In one case, the neutral of a 100A bus duct was damaged, requiring the replacement of 60 ft of bus.)*

6. Where a shared neutral conductor for a 208Y/120 volt system must be used for multiple phases, use a neutral conductor having at least 1.73 times the ampacity of the phase conductors. A convenient way to accomplish this is to use two paralleled neutral conductors, each having the same ampacity as the phase conductors. *(Note that NEC Sec. 310-4 prohibits paralleling conductors smaller than 1/0.)*

7. Where it is not feasible to install double-size neutral conductors, protect the neutral by installing an over-current sensor in the common neutral which will trip an upstream circuit breaker whenever the neutral conductor is overloaded. (This is not a recommendation to interrupt the neutral conductor.)

8. Select three-phase transformers with low internal impedance, preferably in the 3% to 5% range, and always in the delta primary, wye secondary configuration. The transformer should be of three-legged core construction rather than three single-phase transformers or any open delta arrangement.

An open delta transformer is not recommended because it fails to provide a low-impedance path for the third harmonic current, and does not provide the power factor correction which a delta-connected winding can supply.

9. As an alternative to changing the building transformer and its wiring, install one or more delta/wye transformers which are designed for rectifier loads and may be placed in the office or computer room. This may be done either as part of premises wiring or with modular power centers.

10. Although power factor correcting capacitors, which are properly selected and applied on the load side of the transformer, may reduce the harmonic currents which the transformer may otherwise have to carry, this is not a recommended practice. Power system resonances and unexpected high harmonic current may occur unless the system has been specifically designed to avoid them. Each system reconfiguration will require reevaluation of the design.

11. A periodic inspection of the electrical system, particularly after any change in system configuration, should include measurements of phase and neutral currents, temperatures of transformers, their connections, and the connections in the total distribution system. A portable infrared temperature detector is convenient and effective for this purpose. If high temperatures are detected (above 50 degrees C), measurements should be made to determine if excessive currents or loose connections are the cause.

(To avoid problems, all circuit breakers and overcurrent sensing devices must respond to true rms current. Fuses and thermal circuit breakers with bimetals do so inherently. Solid-state circuit breaker trips and relays of special design to assure true-rms response are available from all manufacturers. Use of other than true-rms devices on nonlinear loads can result in premature tripping, or even worse, failure to trip on overcurrent.)

End of CBEMA Information Letter

As more and more incidents of overheating or failures in neutral conductors, transformers, capacitors, and other equipment come to our attention, we feel that the CBEMA recommendations given above should be followed in designing and using electrical systems supplying all types of nonlinear loads. This includes not only computers and business equipment, but also UPS systems, rectifiers, variable-speed drives, solid-state lighting ballasts, and all other rectifier or pulsed-input nonlinear loads. Future National Electrical Code editions must address some of these requirements, especially those for increasing the size of neutral conductors and protecting transformers carrying harmonic currents. ■

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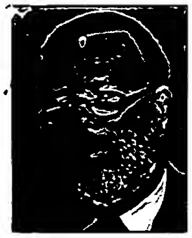
Information that leads to action.



Ray Waggoner

BEWARE OF SINGLE-PHASE HARMONIC INTERACTIONS–PART 1

The popularity of PCs and workstation computers has created wire and transformer overheating problems.

THE trend of replacing mainframe computers with smaller workstation units and PCs has its good and bad points. One of the good points is that we no longer have to worry about the power quality issues associated with large, raised-floor installations. As a computer systems planner once said, "All we have to do is plug in these smaller units into 120V office outlets and, with very small UPSs for backup, we can solve any related power quality problems." We can only wish it could be this easy!

This brings us to the bad points. Although this "downsizing" might appear to solve our power quality problems, we know that *additional* problems are introduced because of the new and different power supply technologies used today. And, the problem sources are on *every* desk, instead of having equipment located in a specific data processing area. Whole bundles of interconnected signal wiring are present. Ground loops are ever present; noise interference through wires as well as through air (radiated interference) is common. And most importantly, harmonic interactions are playing havoc with existing branch circuits and feeders.

Single-phase, switching power supply

The PC or workstation power supply demands large quantities of harmonic currents in addition to 60 Hz work-producing current. The harmonic spectrum will normally consist of 85% third harmonics, 55% fifth, 40% seventh, 25% ninth, and lesser amounts of additional odd harmonic orders. (All of these are percentages of the fundamental 60 Hz current.)

When we sum up all of these currents and the fundamental (by the square root of the sum of the squares), we find that the *total* rms current, or heating value, is *50% greater than the 60 Hz current alone*.

Here is the "thief" on our electrical distribution system, requiring us to have greater capacity to do the same amount of work (watts). As such, it uses up whatever "space" we have in our wiring, panels, and transformers.

When we wire the single-phase devices on a 3-phase, 4-wire system (208Y/120V or 480Y/277V), we observe a new phenomenon: *additive current on the neutral conductor*. While the positive sequence currents (fundamental, seventh, thirteenth, etc.) and negative sequence currents (fifth, eleventh, seventeenth, etc.) *cancel* on the common neutral return wire, the zero sequence, or triplen, currents (third, ninth, fifteenth, etc.) *add or accumulate*. Not only do we have increases in the phase wire heating effect, we have an even larger increase on the neutral wire. This is because all three phase-to-neutral, single-phase loads contribute to the buildup of current on the neutral wire, from 100% to 200% of the phase current level in some instances.

Case history

One interesting situation involved an electrical contractor who was not aware of the problem of harmonic interaction. We were called to an office facility, along with this electrical contractor, to investigate distribution system problems. While measuring the current on each phase of a 225A, 3-phase, 4-wire, panelboard feeder with a true-rms sensing meter, we observed good current balance, with readings in the range of 100A each. Before measuring the neutral current, we asked the contractor what he thought the readings would be on the neutral. Noting that the loads appeared to be balanced on the 3-phase system, he suggested that the neutral current would be very low, perhaps only 3 or 5A.

When we closed the current clamp onto the neutral, the reading was 195A. Upon seeing this, the contractor exclaimed, "Your meter's broke!" "What about the phase readings?" we asked. The contractor then replied that they were correct but that the meter was definitely "broke" for the neutral reading. His reasoning was that all 60 Hz currents balanced on the phase wires will cancel on the neutral. And he was right. What we were measuring on the neutral, however, was the third, ninth, fifteenth, etc. harmonic currents and, as the contractor originally expected, *very little* 60 Hz current. Obviously, he was unaware and certainly unknowledgeable of the harmonic interaction problem.

• • •

Next month, we'll continue our discussion of this case history and follow up with some mitigation techniques that can be used to counter the problem of single-phase harmonic interaction. ■

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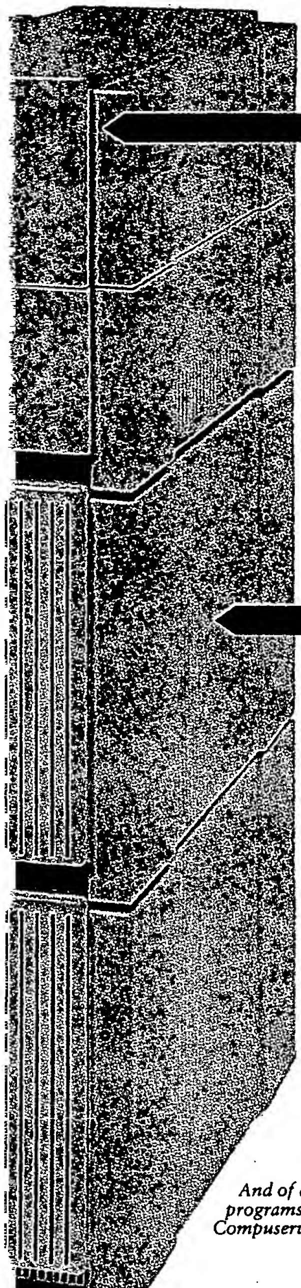

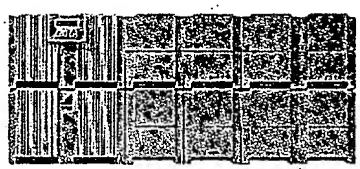

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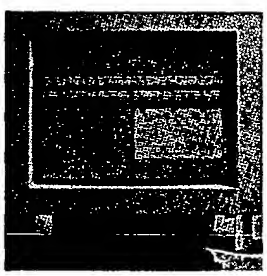

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CIRCLE 12 ON READER SERVICE CARD

Ray Waggoner

BEWARE OF SINGLE-PHASE HARMONIC INTERACTION–PART 2

The popularity of PCs and workstation computers has created wire and transformers overheating problems.

IN Part 1, we discussed some of the properties of single-phase harmonics, particularly the peculiar currents demanded by the switch mode power supplies found in PCs, workstations, process control equipment, telecommunications, and lighting. We also discussed the symptom of high neutral currents. Remember our contractor whose explanation for expecting low currents on the neutral was based on an undistorted 60-Hz sine wave and balanced loads on a 3-phase, 4-wire system. Instead, the currents were no longer just 60 Hz, but a mixture of harmonic orders, predominantly multiples of the third harmonic current (third, ninth, fifteenth, etc.). These currents from each phase-to-neutral load were adding on the common wire rather than canceling.

While the power supply industry is already changing to correct for this current spectrum, we are still left with a great many of the problem devices in operation today, and for some time to come. Our task in the foreseeable future can be broken down into three components.

- Be alert to the possible accumulation of higher frequency currents.
- Be able to predict what design methods should be used to handle our present problems.
- Mitigate ("do away with" by harmonic canceling methods) those harmonics that may cause dangerous overheating in delta-wye transformers and neutral conductors.

This task is doubly important because first, these single-phase device currents travel on all "common return" wires: both 277V and 120V neutrals. Secondly, on many systems, we are handling 3-phase harmonic orders on the phase wires as well.

Case history continuation

Our case study begun in Part 1 is actually a verification of typical conditions in commercial buildings today. We were checking a single panel in an existing building that had just been "converted" to powering nonlinear loads (loads having "switching" power supplies). We also were making a comparison of currents of "old" and "new" devices. The reason for the check-out was to predict some of the owner's future needs in a building addition currently under way. With these reading comparisons, we would be ready to consider the needs of the new systems.

Most of the construction team was under the impression that a large quantity of "old" style devices was to be used in the new building. This would have meant workstations with "dumb" terminals, expected to draw only 0.2A per station with relatively little harmonic distortion. In other words, a relatively "linear" type of load. Instead, the department head responsible for the workstations informed the group that the computers selected were "intelligent" PCs, meaning that they were similar to the devices being powered by the "converted" panelboard at the existing building.

Our first fear was that there was a lack of power for the five floors of the new building, since the "new" devices were rated five times more powerful than the "old", and there were to be 600 units total! Further discussion revealed that there was ample power available in the building riser and floor distribution. However, *no* preparation was made for the large amount of 180 Hz harmonic current that would circulate in the wiring system. As the workstations would be brought online, the heating effect on the neutrals of branch circuits and feeders as designed would be excessive. Also, no provisions were made to keep these harmonics from going everywhere in the building, and no calculations were yet conducted on damaging voltage drops at the several harmonic orders.

Evaluating possible solutions

The owner's committee was now ready to examine what had been done to "convert" panels and wiring in the old building to handle the "new" device loads in the new building. An

ideal examination point proved to be one area of the old building having a large quantity of "new" PCs. The facility personnel saw that the power rating of the "new" devices was five times larger than that of the old systems and thus made sure that the new loads could be handled. First, they took other loads off the "converted" 225A panel. Second, they increased the size of the phase and neutral conductors. In other words, they had "rewired" to compensate for the addition.

During these discussions, the point was made that not all of the "new" PCs would be installed at the same time. Thus, the owner could "live with the present design for now, and then change wiring in the future when needed on a station-for-station basis", rather than undertake a major change in the wiring of the new building. It then was decided to check the costs for the conversion of the few circuits in the old building to see if this would be an economical approach.

The cost for "converting" the old panelboard and its branch circuits was $1500 per circuit. The committee now knew it had to find a better plan! (Even with only 300 of the 600 units to be "converted", the cost of $450,000 for doing circuits one at a time was prohibitive).

Where was the P.E.?

You might ask, "What was their professional electrical engineer doing all this time; didn't he/she prepare the committee for this event?" The question may seem appropriate, since it's the designer's job to direct the specifications and layout of a proper system for the expected devices. But, notice the "technical void" that appears in this example. First, the designer stands ready to do his sizing and layout based on the "misinformation" provided by the end user that the "old" units are to be reused. Second, the owner, in the supervision of construction, is not aware of the fact that "new" units are to be used and, as a result, does not know their operating characteristics. Thus the designer is "blind sided" and must scurry to properly prepare for the operation of the changed system!

When this problem was addressed at a later meeting, this very fine P.E. told the committee, "If you can characterize your devices for me, I'll be able to complete a design to your satisfaction." Now the problem centered on the decision as to what design methods to use.

• • •

Next month we'll complete the story of how the design was changed to handle the "new" units on every floor, and we'll share some additional examples of methods for coping with third harmonic currents from single-phase devices. Also, a new method of canceling the high frequency demands of the switching power supply will be discussed. ■

Call for Case Histories

To address the ever-increasing need for information on power quality and harmonics, *EC&M*, in conjunction with Fluke Corp., is initiating a call for case history papers. Each paper should include details such as symptoms, troubleshooting techniques, problem diagnosis (poor power quality or presence of harmonics), and test equipment. Also included should be pertinent information about the affected power distribution or process system.

Prizes, courtesy of Fluke Corp., will be awarded to those submissions determined to be the best in the following categories:

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John DeDad, Editor-in-Chief, *EC&M*, White Plains, NY.

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John Matthews, Principal, John Matthews & Assoc., Atlanta, GA.

Charles Newcombe, Sr. Product Planner, Fluke Corp., Everett, WA.

John Sullivan, Power Engineering Consultant, Sullivan Consulting Group, Half Moon Bay, CA.

Alan Wallace, Associate Professor, Electrical and Computer Engineering Dept., Oregon State University, Corvalis, OR.

The winning submittals will be published in *EC&M* under the submitter's byline.

All of the submitted material is intended for possible use in *EC&M* as well as for product application information by Fluke Corp.

Please send your case history to:

EC&M
707 Westchester Ave.
Suite 101
White Plains, NY 10604
Attn: PQ Case History
Deadline for submittals:
August 19, 1994

BEWARE OF SINGLE-PHASE HARMONIC INTERACTIONS - PART 3

Ray Waggoner

Methods of coping with and eliminating triplen harmonic currents can help alleviate transformer and neutral conductor overheating problems.

IN Part 2, we saw how the proposed installation of 600 new style workstations brought fears of widespread harmonic distortion in a new addition to an existing building. Specifically, we were concerned about the amount of zero sequence currents adding onto the neutral conductor. Remember, these currents can be twice the phase currents.

Demountable partition wiring

The problem became even more significant: for the purpose of layout flexibility, the Owner intended to use manufactured, prewired office partitions throughout the new addition. As a result, the workstations could be located anywhere. When we examined the different sizes of loads the Owner wished to power from the partitions, we found we needed some help from the partition manufacturing industry. Specifically, how could we counter the neutral current problems in the partition wiring?

RMS value = 1.42A
Total harmonic distortion = 130.0%

Harmonic value	
1 = 0.87 A	
2 = 0.01 A	1.10%
3 = 0.77 A	89.50%
4 = 0.02 A	2.40%
5 = 0.62 A	72.00%
6 = 0.03 A	3.40%
7 = 0.44 A	51.00%
8 = 0.03 A	4.00%
9 = 0.25 A	29.00%
10 = 0.03 A	4.00%
11 = 0.10 A	12.00%
12 = 0.02 A	3.30%
13 = 0.01 A	1.40%
14 = 0.01 A	2.20%
15 = 0.05 A	6.70%
16 = 0.00 A	0.80%
17 = 0.06 A	7.70%
18 = 0.00 A	0.20%
19 = 0.04 A	5.30%

Table 1. Typical PC power supply's harmonic spectrum without tuned filtering.

RMS value = 0.98A
Total Harmonic distortion = 51.1%

Harmonic value	
1 = 0.86 A	
2 = 0.00 A	0.60%
3 = 0.15 A	17.30%
4 = 0.00 A	0.30%
5 = 0.29 A	33.70%
6 = 0.01 A	0.14%
7 = 0.17 A	20.70%
8 = 0.00 A	0.40%
9 = 0.13 A	15.90%
10 = 0.00 A	1.10%
11 = 0.09 A	10.90%
12 = 0.00 A	0.80%
13 = 0.10 A	11.90%
14 = 0.00 A	0.90%
15 = 0.07 A	8.00%
16 = 0.00 A	0.50%
17 = 0.08 A	9.40%
18 = 0.00 A	0.70%
19 = 0.07 A	8.20%

Table 2. Typical PC power supply's harmonic spectrum with plug-in type tuned filtering.

Thankfully, many partition manufacturers were already aware of overheated neutrals and had included in their designs double sized shared neutrals or individual neutrals for each phase wire. They also recognized the need for separating conventional duplex outlets and IG style outlets (for equipment requiring isolated grounding). The Owner was then able to select the style of partition wiring best suited for his proposed installation.

Distribution wiring

We could now focus on the rest of the power distribution system. First, there was the 3-phase, 4-wire, delta-wye transformers at each floor. We decided to increase their individual capacities from 75kVA to 150kVA. (At the time of this project, the k-factor transformer was not available.)

Second, we increased the bus sizing of each branch circuit panelboard from 225A to 400A. Also, a 400A neutral bus was added.

Third, we provided double-sized shared neutrals on circuits from the panelboards to the junction boxes where the "whip" connections to the partitions were to be made.

Canceling harmonic currents upstream

Let's review how triplen harmonic currents (3rd, 9th, 15th, etc.) generated by PCs and workstations (nonlinear loads) progress through a distribution system. The shared neutral in the branch circuit wiring carries these currents *from* the nonlinear loads, through the panelboard, to the delta-wye transformer. Here, these currents pass through the wye (secondary) winding but are trapped in the delta (primary) winding, where they circulate. This is both good news and bad news.

The good news is that the triplen harmonics are contained within the transformer and are not transmitted upstream beyond the transformer onto other distribution systems. Thus, we have prevented these harmonics from migrating further and interacting with

other parts of the building.

The bad news is that the transformer now requires proper sizing in order to carry this "additional" current. Otherwise, it would overheat and possibly result in severe equipment and facility damage. This is the basic reason for the k-factor transformer design. This type of transformer's windings and core are "beefed up", so to speak, to accommodate these higher frequency currents. Because the triplen harmonics don't pass through the primary winding, the overcurrent protective device ahead of the transformer will not respond to them; thus, the transformer must be protected in other ways.

Coping with the problem

All of the above discussion has centered on increased sizing to handle triplen harmonic currents. We've discussed redesigning, rearranging, and/or oversizing because these currents "steal" space from our electrical distribution system.

We also could install a current transformer (CT) on the neutral conductor of the panelboard power feeder. This CT would send an trip signal to a shunt-trip breaker located on the primary of our delta-wye transformer when the neutral current approaches conductor rating limits.

But what are we really doing here? Is the problem really gone? The answer is NO; we're just *coping* with it. We're protecting ourselves *from* the problem. Suppose we change directions. Suppose we look toward *lowering* or *getting rid of* these harmonic currents. We would then be returning our system back to a true 60 Hz system. We can approach this ideal condition by using tuned filters.

Eliminating the problem

Table 1 (see page 17) shows a harmonic current spectrum of a typical PC power supply. We see that the Total Harmonic Distortion (THD) is high (130%). We also see that the total rms current is 1.42A versus 0.87A for 60 Hz current (1st harmonic). In other words, the system must carry the higher value in heating and overall capacity (1.42A) while the work production is actually at the lower level (0.87A).

Table 2 (see page 17) shows a harmonic spectrum of this same PC power supply, but with a new plug-in tuned filter. Note that the THD decreases to 51.1% and the total rms current drops to 0.98A. Thus the system is required to carry 31% less heating and overall capacity. Also note that the 3rd harmonic content is reduced from 89.5%, as shown in Table 1, to 17.3%. ■

Please circle the appropriate Reader Service Number on the provided Reader Service Card that best describes your feelings on the usefulness of this article.

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Please send your case history to:

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By popular request, we are extending the deadline to:

September 30, 1994